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Corn stover collection prior to biogas production – Evaluation of greenhouse gas emissions

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ABSTRACT

Sustainability in terms of greenhouse gas (GHG) emission saving for biogas production and utilisation is defined by Renewable Energy Directive (RED) and amending documents. The method for determination of GHG emissions defines that, when crop residues are evaluated, only those emissions originating from collection should be considered in the balance. As a result of such approach, lower emissions could be assigned to life cycle of crop residues, due to neglected effects of nutrients removal via residues and digestate management practice. Objective of this study was to evaluate GHG emissions of corn stover collection, intended for biogas production. The evaluation was performed strictly following the method defined in RED, but also by additional scenarios, to consider effects of nutrients removal and digestate management. GHG emissions of corn stover collection were in the range of 14,000 gCO_{2eq}/tDM to 150,000 gCO_{2eq}/tDM depending on the scenario. Lowest emissions are associated with scenario completely in line with the method stated in RED and highest when digestate is used on other fields than those from where corn stover was collected and if removed nitrogen, potassium and phosphorus nutrients are compensated by mineral fertilisers. Further investigations should be oriented to give improved data about nitrogen removal via crop residues, its transformation during anaerobic digestion and emission factors for digestate application. These data could considerably improve evaluation of biogas production from crop residues in terms of GHG emissions.

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1. Introduction

Corn stover, crop residue of corn grain production, is the most abundant agricultural biomass in many Danube region countries in central and south-eastern Europe (Martinov et al., 2016). It is potential source for generating renewable energy such as biogas. It is still mostly unused due to its lignocellulosic nature which is unsuitable for fermentation (Lizasoain et al., 2017). There are some pre-treatment technologies, *e.g.* enzymatic treatment (Schroyen et al., 2014), steam explosion (Lizasoain et al., 2017; Shafiei et al., 2013) and other physical treatments (Theuretzbacher et al., 2015), mostly in the stage of early commercial maturity. They are used for breaking of lignocellulosic structure in corn stover and similar crop residues, prior to biogas production. By expansion of these technologies it is reasonable to expect that corn stover utilisation as a biogas substrate will significantly increase in the future.

Production and use of biofuels for transport, such as biomethane, bioliquids and biomass for electricity, heating and cooling should fulfil sustainability criteria defined by Renewable Energy Directive (RED) and its amending documents (European Commission, 2009, 2017a, 2017b). For biofuels, a greenhouse gas (GHG) emission saving is the most challenging criterion due to fact that the saving in comparison to a fossil fuel comparator has to reach at least 60%. In 2021, this value will be 70%. For biomass used for electricity generation, heating and cooling, GHG emission saving will have to be minimum 80% in comparison to the fossil fuel comparator. Values of the fossil fuel comparators for biofuels and biomass used for electricity are 94 and 183 gCO_{2eq}/MJ, respectively. The RED is providing, in Annex V, a method which should be used for determination of the actual GHG emission savings for biofuels. It can also be used in an adapted form for determination of the same value in case of biogas utilisation for electricity, heating or

Abbreviations: BB, Big bales; DM, Dry matter; EONR, Economically Optimum Nitrogen Rate; GHG, Greenhouse gases; ILUC, Indirect Land Use Change; IPCC, Intergovernmental panel for climate change; LCA, Life Cycle Assessment; LCI, Life Cycle Inventory; LCIA, Life Cycle Impact Assessment; PE-HD, Polyethylene High Density; PE-LD, Polyethylene Low Density; RB, Round bales; RED, Renewable Energy Directive; SOC, Soil Organic Carbon.

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cogeneration. The aim of this method is to assess the emissions within different life cycle phases of the end product, *e.g.* biomethane or electricity, and to compare them with the mentioned fossil fuel comparator. These phases are: cultivation or extraction of raw material (collection of crop residues), production, transport and distribution and use.

By implementation of the ILUC (Indirect Land Use Change) Directive 1513/2015 (European Commission, 2015), amended RED incentivise the production of the second generation biofuels made from, among other, non-food cellulosic materials, such as corn stover, by limiting the share of conventional, first generation, biofuels to 7%. Also, the amendments set a reference target value of minimum 0.5% for advanced biofuels which member states should have adopted by April 2017 and state that contribution of these biofuels counts double to the national targets. Another measure for promotion of agricultural crop residues, defined by RED, is that the GHG emissions are zero up to the process of their collection. That should contribute to much easier fulfilment of the GHG emission saving criterion for all energy utilisation pathways of crop residues. It practically means that, according to the RED method, emissions associated with the extraction phase or cultivation of raw materials are only those made as a consequence of agricultural operations engaged in the crop residue collection. The European Standard EN 16214-4: 2013 (European Committee for standardization, 2013) has been developed to assist in the implementation of the RED method and confirms its compliance with the principles of Life Cycle Assessment (LCA). Giuntoli et al. (2015) have determined GHG emission savings for several energy utilisation pathways of biogas, and these values are reported as a default GHG emission saving values stated in RED amending documents (European Commission, 2017a, 2017b).

During analysis of wheat straw based bioethanol, Whittaker et al. (2014) have done critical overview of the RED method and claimed that it is not in line with the European Common Agricultural Policy because of the impact that the removal of crop residues has on the soil fertility preservation and erosion protection. The removal of crop residues can be manifested through additional GHG emissions due to application of mineral fertilizers used to compensate nutrients removed from soil via residues (Cherubini et al., 2009; Cherubini and Ulgiati, 2010; Whittaker et al., 2014). In case of biogas production and utilisation, impact of crop residues removal is directly influenced by the management of a digestate – a co-product of biogas production. One case would be that this organic fertilizer is distributed on the same agricultural field where crop residues were taken. Second would be that it is used on another fields. In combination with rules for application of RED method, several problems arise that could assign lower overall GHG emissions to analysed system.

In the first case, closed loop system is achieved, and except nitrogen lost during application of digestate (volatilisation of ammonia and direct emissions of nitrous oxide), all nutrients are returned to the field. Problem arises due to lost nitrogen since additionally fertilisers used for its compensation would be assigned to a following crop. For substrates, like corn silage, this is not the case which is thoroughly explained in (Giuntoli et al., 2015). In the second case, when digestate is used on other fields, digestate represents co-product and some GHG emissions need to be assigned to it due to allocation envisaged by RED method. This is logical approach, but again remains the question of additionally applied fertilizer. How to include those emissions which would be the consequence of application of fertilisers intended for nutrients compensation. RED method, due to the rule that GHG emissions are zero up to the process of crop residue collection, does not enable inclusion of such emissions. Adams et al. (2015) emphasized deficiencies of RED method associated to allocation of GHG emissions between biogas and digestate for common substrates, *i.e.* manure and corn silage, but obviously problem is even more complex if crop residues are used as a substrate. Solution could be to assign to the analysed system GHG emissions arising from removal of the corn stover from field combined with applied digestate management pathway. These emissions would be assigned to phase collection. Of course, it is not clear if these additional emissions could have major impact on sustainability of corn stover use as a biogas substrate. The value of these additional emissions is unknown and it is not fully clear which ones should be included.

Evaluation of the collection phase of corn stover, which is intended to be used for biogas, in terms of the GHG emissions without accounting possible long-term sustainability impact that its removal has on the soil, is deficiency of the RED method. Appropriate inclusion of these emissions needs to be based on scientific backgrounds for the impacts of corn stover removal. Objective of this study is to determine the GHG emissions associated with the collection of corn stover prior to biogas production in accordance to the RED method but also by taking into account GHG emissions which are consequence of nutrients removal. In this way will be provided backgrounds for better understanding possible improvements of the RED method which could more precisely assess the GHG emissions savings related to utilisation of corn stover and other crop residues.

2. Material and methods

2.1. Material

2.1.1. Procedures of corn stover collection

Stover collection can be organized in such a way that incorporates several, two or only a single pass over the field. The appropriate stover collection technique should be selected depending on grain harvest efficiency, an increase of the grain-loss rate and contamination by soil, *i.e.* soiling, expressed as ash content (about 5% of ash presents mineral matter of unsoiled corn stover). Based on a detailed survey of the relevant literature (Perlack and Turhollow, 2002; Shinners et al., 2007a, 2007b, 2009, 2012), it is concluded that the two-pass procedure is the most appropriate one to collect stover for biogas production, since it is more efficient from energy aspect than collection in several passes and does not influence harvest efficiency and grain-loss rate as by single pass collection. In comparison to the multi-pass, the two-pass approach is also preferable in terms of soiling. Nevertheless, this harvest procedure results in higher rate (up to 90%) of harvested cobs and husks.

For two-pass procedure, the special header with chopper–windrower is needed, *e.g. Cornrower* developed in USA and presented in (Shinners et al., 2012; Straeter, 2011), and recently developed and offered by one European manufacturer. Formed windrow–swath is a good pad for material dropping out of harvester, cobs, husks and snapped leaves. It is assumed that the use of such device would raise the usual harvester's fuel consumption of 28 L/ha (Cooperative Union of Vojvodina, 2014) by app. 33% (Straeter, 2011). However, since the corn stover shredding can be seen as a part of the corn grain growing cycle, only fuel consumption for windrow forming is included in the stover collection analysis. It is assumed that this amounted about 20% of the additional consumption, or 2 L/ha. The process "Combine harvesting, CH" from the *Ecoinvent* was used as a basis to model the windrow forming phase.

The baling of windrowed material in the form of big (rectangular) bales (BB) or round bales (RB) is the second harvest pass. Both types of balers are considered since they are commonly used. Baling (pick-up) efficiency differs for different corn stover parts, but

in total it approximately rates 60% for both balers (Shinners et al., 2012, 2007b). Based on the usual bale size and literature data concerning density of baled stover (Shah et al., 2011; Shinners et al., 2007b), the following bale characteristics were used: dimensions 1.2/0.9/2.4 m with a dry matter (DM) density of 110 kg/m^3 for BB, ϕ 1.5/1.2 m and a DM density of 90 kg/m^3 for RB. Baling includes consumption of plastic twine for BB or net wrap for RB. According to the *Ecoinvent* process "Baling, CH", for one RB is needed 1 kg of plastic material which seems to be overestimated. Based on personal communication with agricultural producers, for a BB, app. 0.41 kg of plastic twine in needed while for a RB is needed app. 0.16 kg of plastic net wrap. These were the values applied for this study. The associating emissions originating from production of these plastic materials were from the *GaBi professional* process "Polyethylene high density granulate (PE-HD), RER".

Emissions associated with the bales loading/unloading were based on the *Ecoinvent* process "Loading bales, CH". For the storage phase, primary storage and storage at the location of biogas plant were considered. It was assumed that bales are covered by a special plastic tarp made of low density polyethylene (LDPE), with a specific mass of 130 g/m^2, dimensions 12.5 m × 9 m and a life span of 5 years. RB were forming pyramidal stack with three bales in the first row, while the stack formed from BB had four bales' layer of 0.9 m height, placed in three stakes with an additional bale in the middle stake in order to form the shape of a roof (Shah et al., 2011). Emissions made as a consequence of the tarp usage are originating from its production, presented here by using *GaBi professional* process "Polyethylene film (PE-LD), RER".

The supply chain of the baled stover includes transport from fields to primary storage and between the primary storage and a biogas plant where the stover is used. The primary storage site is located close to the fields resulting in a transportation distance of up to 5 km (Bojić et al., 2013). For the purpose of this study it was considered that collected stover is transported by a tractor and two trailers. Capacity of such trailers is 24 BBs or 26 RBs. A considered transportation distance between the primary storage and the biogas plant was 20 km. For presumed transport was selected a truck with 27 t of payload capacity - 33 BBs or 30 RBs. For sensitivity analysis the transport distance varied. Distance of 100 km was selected, as upper limit based on supply economy. Usually, it is common to purchase biogas substrates available in the vicinity of a plant. So, transport distance longer than 100 km is unrealistic and therefore not applied for this study.

After anaerobic digestion of corn stover, digestate is generated and needs to be appropriately applied on agricultural fields. Quantity of generated digestate depends on biogas yield, and yield depends on corn stover quality, application of pre-treatment technology, operational parameters during digestion and initial moisture content. Digestate can be separated in liquid and solid fraction. For this study and scenarios the digestate management was included in system boundaries. It was considered that entire amount of digestate is transported and distributed in liquid form by a liquid manure spreader equipped with a splash plate which is the most common technique in Serbia. Transport of digestate is not included in the analysis following the approach of Giuntoli et al. (2015). For emissions emerged as a consequence of actual agricultural operation digestate spreading are used those from *Ecoinvent* – "Liquid manure spreading, by vacuum tanker, RoW". For nutrient content of the digestate it was assumed that entire K_2O and P_2O_5 remains in digestate after digestion but for nitrogen content was adopted that 6% is lost during the digestion. For nitrogen lost during storage, emission factors stated in (IPCC, 2006a) were used. GHG emissions during digestate spreading are also included. According to Wulf et al. (2002), emissions of CH_4 during digestate spreading are insignificant in comparison to those of N_2O emitted directly or indirectly. Based on these findings, emissions of CH_4 from digestate spreading were neglected. For calculation of direct and indirect N_2O-N emissions, IPCC emission factors were applied. The same factors were used to determine the quantity of mineral fertilizer that should be used to compensate the lost nitrogen in digestate. This lost nitrogen from digestate was assumed to be compensated by urea and for those GHG emissions made during its application, again IPCC emission factors were used (IPCC, 2006b). The amounts needed for compensation of lost phosphorus and potassium nutrients were considered as input into the analysed system in the form of mineral fertilizers potassium-nitrate and single-superphosphate. Associated emissions from production of fertilizers were based on the *Ecoinvent* processes "Urea production, as N, RER", "Potassium nitrate, as K_2O, at regional storehouse, RER" and "Single superphosphate, as P_2O_5, at regional storehouse, RER".

Regarding materials consumption for the agricultural processes, only diesel consumption was considered with characteristic emissions based on *Ecoinvent* process "Diesel, at regional storage, RER", while other emissions originating from a machine production and maintenance, buildings (sheds), lubricants, *etc.*, were not included.

2.1.2. Characteristics of corn stover

Amount of collected stover depends on biomass yield and collection procedure applied. For good agricultural practice applied, common usable yield of corn stover in Serbia (total aboveground mass without lowest 20 cm of stalks) is 9.2 tDM/ha (Golub et al., 2012; Martinov et al., 2015). Amount of harvested by two-pass procedure would be 6.3 tDM/ha. This value is used as basic one for this study, but in order to determine how different values of this parameter influence the result, sensitivity analysis was also done. Harvestable corn stover yield depends on agro-ecological conditions and it varies from 4.3 to 8.4 tDM/ha (Martinov et al., 2015).

The content of nutrients is lower in upper parts of stalks and cobs/husks and that is why these parts are more desirable for collection and utilisation as energy source (Johnson et al., 2010). It is also changeable during growing period and therefore can be influenced by a time of the collection (Sawyer and Mallarino, 2012). Simplified, nutrients removal rates were calculated based on the nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O) content of the corn stover, 6.2 g/kgDM, 2.3 g/kgDM and 14.0 g/kgDM, respectively, as reported by (Cook and Shinners, 2011) for stover collected by applying two pass harvest procedure. It should be emphasized that here was considered amount of total nitrogen, dominantly in form of complex bio-molecules, *i.e.* amino acids.

It was adopted that stover has 75% DM content and that there are no changes of it during the entire collection procedure. For material flow, it was considered loss of corn stover's DM. Values for DM loss vary significantly for different types of storage practices, weather conditions, initial DM content, existence of a standing platform, but a general value for DM loss for both bales types is around 4% of initial DM content (Schon et al., 2013; Shah et al., 2011; Shinners et al., 2011) that was applied in this study. Loss of DM during storage occurs in the form of GHG. Since emissions of CH_4 and N_2O are insignificant and dominantly DM is lost as biogenic CO_2 (Emery and Mosier, 2015), all gaseous emissions from loss of DM were excluded from the LCI.

Applied was that 350 m^3/tDM of biogas is produced from corn stover with methane content of 52% (v/v) (KTBL, 2010), and that for every dry ton of corn stover 0.675 t of digestate is generated (including moisture contained in corn stover).

2.2. Methods

2.2.1. System boundaries and analysed scenarios

Boundaries of the analysed system are based on the RED

method. Equation (1) summarizes GHG emissions from lifecycle phases of biogas utilisation.

$$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr} \quad (1)$$

where: E – total emissions from the use of the fuel (biomethane) or emissions from the production of the fuel before energy conversion (biogas for electricity), e_{ec} – emissions from the extraction or cultivation of raw materials; e_l – annualised emissions from carbon stock changes caused by land-use change; e_p – emissions from processing; e_{td} – emissions from transport and distribution; e_u – emissions from the fuel in use; e_{sca} – emission saving from soil carbon accumulation via improved agricultural management; e_{ccs} – emission saving from carbon capture and geological storage; e_{ccr} – emission saving from carbon capture and replacement.

Element of the equation, relevant for this study, is e_{ec}. Other elements are associated to biogas production and utilisation, transport, storage and distribution of materials, improved agricultural management in case of some biogas substrates *e.g.* manure. These elements are not in focus of this study. Corn stover collection, e_{ec}, includes following operations which were already described in chapter 2.1: windrow forming, baling, manipulation with the stover on a field and storages (loading, unloading and moving), transport of corn stover and its storage. Transport of agricultural raw materials to the biogas plant is, according to the RED method approach described in (European Commission, 2010), included in the collection phase.

Furthermore were considered emissions originating from additionally applied mineral fertilizers and digestate management. For the inclusion of nutrients removal into the similar studies of GHG emissions (Kral et al., 2016; Luo et al., 2009; Murphy and Kendall, 2013; Pourbafrani et al., 2014; Spatari et al., 2005; Whitman et al., 2011), usually were considered three primary macronutrients, nitrogen, potassium and phosphorus and their additional application in the form of mineral fertilizers. This approach seems to be logical. However, the question arises whether it is justified in the case of corn stover removal. The main reason for the additional application of mineral fertilizers is reaching an optimal yield of a following crop. There are indications that, when corn stover is partially collected, *i.e.* about half of the total aboveground mass, there is no negative impact on the yield of following crop (Johnson et al., 2013). The yield may be even higher in comparison with a case when stover is left on a field (Karlen et al., 2014). Sawyer and Mallarino (2012) made a similar claim and associate it with a decrease of the Economically Optimal Nitrogen Rate (EONR). The decrease of EONR is explained by less addition of carbon to soil for microbial processing. Similarly, increase of the EONR is the consequence of remaining complete corn stover on the field (Coulter and Nafziger, 2008). However, soil characteristics, environmental conditions and applied agricultural measures within region under the scope of a study should be taken into account, but it can be assumed that by removing up to 75% of the corn stover there will be no significant impact to the soil's nitrogen balance (Khanal et al., 2014) and only additional application of mineral fertilizers which contain potassium and phosphorus are sufficient to maintain required soil nutrients needs (Adler et al., 2015). Reason is availability of nitrogen contained in corn stover. It is mainly in form of amino acids and not in mineral form suitable for plants.

Since several different cases are possible due to consideration of nutrients flows and digestate management, following scenarios, presented in Table 1, were analysed within this study:

2.2.2. Life cycle assessment

The software package *GaBi 6* is used for the system modelling and performing the life cycle impact assessment (LCIA). It included the integrated *Ecoinvent* 3.1 (Wernet et al., 2016) and *GaBi professional* databases. System boundaries incorporated adequate generic processes and material flows which could be considered as representative for geographical region under the scope, *i.e.* Serbia, but also for other European countries. Used processes were stated in chapter 2.1. In the case of necessity, processes were modified in such a way to be completely in line with the RED method and typical example is no consideration of emissions from the equipment manufacturing associated to the used processes. As a functional unit (FU), 1 tDM of corn stover was selected.

The results of the Life Cycle Inventory (LCI) contain data about all possible emissions of GHG from the analysed system, but here, in line with the RED, only emissions of carbon dioxide –CO_2, methane –CH_4 and nitrous oxide –N_2O were selected. In the LCIA step, these emissions were classified and characterized in order to determine their impact on the appropriate impact category. The LCIA is evaluated using CML 2001 (version April 2015) developed by the Institute of Environmental Sciences at Leiden University, and chosen impact category is Global warming potential (GWP 100 years) excluding biogenic carbon. In this LCIA method global warming potential factors in accordance to the RED method were used: CO_2

Table 1
Defined scenarios.

Scenario	Association with RED method	Consideration of digestate management	Consideration of nutrients in corn stover		
			Nitrogen	Phosphorus	Potassium
S1	Yes, completely in accordance with RED method rules	No	No	No	No
S2	Partially, expansion of system boundaries on digestate management	Yes, applied on the same field from where stover was collected	No	Yes, return via digestate on the same field from where stover was collected	Yes, return via digestate on the same field from where stover was collected
S3	Partially, expansion of system boundaries on digestate management	Yes, applied on the same field from where stover was collected	Yes, return via digestate on the same field from where stover was collected + compensation of nitrogen lost due to volatilisation and nitrous oxide emissions	Yes, return via digestate on the same field from where stover was collected	Yes, return via digestate on the same field from where stover was collected
S4	Partially, expansion of system boundaries on nutrients compensation	No, applied on other fields	No	Yes, compensation of lost nutrient by mineral fertilisers	Yes, compensation of lost nutrient by mineral fertilisers
S5	Partially, expansion of system boundaries on nutrients compensation	No, applied on other fields	Yes, compensation of lost nutrient by mineral fertilisers	Yes, compensation of lost nutrient by mineral fertilisers	Yes, compensation of lost nutrient by mineral fertilisers

Table 2
GHG emissions in gCO_{2eq}/tDM of corn stover for analysed scenarios.

Scenario	S1		S2		S3		S4		S5	
	BB	RB	BB	RB	BB	RB	BB	RB	BB	RB
Windrow forming	909	909	909	909	909	909	909	909	909	909
Windrow forming, diesel	148	148	148	148	148	148	148	148	148	148
Baling	2284	2284	2284	2284	2284	2284	2284	2284	2284	2284
Baling, diesel	370	370	370	370	370	370	370	370	370	370
Bales moving/loading/unloading	1872	2798	1872	2798	1872	2798	1872	2798	1872	2798
Bales moving/loading/unloading, diesel	302	452	302	452	302	452	302	452	302	452
Plastic twine/net wrap	2886	1683	2886	1683	2886	1683	2886	1683	2886	1683
Plastic foil	708	688	708	688	708	688	708	688	708	688
Digestate application	–	–	514	514	514	514	–	–	–	–
Digestate application, diesel	–	–	83	83	83	83	–	–	–	–
Digestate application, N_2O emissions	–	–	–	–	39,685	39,685	–	–	–	–
Tractor transport	705	973	705	973	705	973	705	973	705	973
Tractor transport, diesel	114	157	114	157	114	157	114	157	114	157
Truck transport	2998	4677	2998	4677	2998	4677	2998	4677	2998	4677
Truck transport, diesel	505	788	505	788	505	788	505	788	505	788
Mineral fertilizer, K_2O	–	–	–	–	–	–	12,611	12,611	12,611	12,611
Mineral fertilizer, P_2O_5	–	–	–	–	–	–	6363	6363	6363	6363
Mineral fertilizer, N	–	–	–	–	28,897	28,897	–	–	48,337	48,337
Mineral fertilizer, N_2O emissions	–	–	–	–	40,866	40,866	–	–	68,358	68,358
Total	13,801	15,926	14,398	16,523	123,847	125,972	32,775	34,901	149,470	151,596
Total, gCO_{2eq}/MJ	2,0	2,3	2,1	2,4	17,9	18,2	4,7	5,1	21,6	21,9

BB – big bale, RB – round bale, S – scenario.

– 1; CH_4 – 25; N_2O – 298.

3. Results and discussion

The RED is providing an estimated disaggregated default value for collection of wheat straw, which can be used for determination of the GHG emissions saving typical for bioethanol based on this substrate. It rates 1.8 gCO_{2eq}/MJ of produced bioethanol. Since it was adopted that 6 kg of bone dry straw is needed to produce 1 L of bioethanol with energy content of 21 MJ/L (Edwards et al., 2017), it follows that this phase, without transport of straw, emits approximately 6300 gCO_{2eq}/tDM. If 50 km transport is included, then total emissions are 7.3 gCO_{2eq}/MJ, *i.e.* 25,550 gCO_{2eq}/tDM. Comparable results were expected for corn stover.

GHG emissions classified per analysed scenarios are presented in Table 2. S1 that represents GHG emissions of corn stover collection completely in accordance with rules of RED method as expected has the lowest emissions due to smallest number of operations included into system boundaries. Emissions are roughly in the range of 13,800 to 16,000 gCO_{2eq}/tDM depending on the form of collected stover. Collection in the form of BB is showing, to some extent, lower emissions mainly due to better utilisation of the vehicles' transport capacities. Transport is contributing from 30 to 40% of entire emission balance for the analysed case, Fig. 1. Of course, it depends from selected transport distance. Combined agricultural operations just for collection emit 9479 gCO_{2eq}/tDM which is comparable with the result for straw collection stated in RED. Agricultural operation with the highest contribution to the GHG emissions balance is baling. Interesting is that use of plastic net wrap or twine contributes up to 50% of GHG emissions in this phase. The rest of emissions in this phase are result of performing baling and emissions originating from production of used diesel. Emissions from windrow forming and bales manipulation are lower in comparison to baling. Since windrow forming is here considered as a part of grain harvest, *i.e.* in the same pass on the field, associated emissions are low due to low diesel consumption for this operation. In practice is not rare case that windrow is formed by additional pass, by crop residues shredder, so expected emissions from this process would definitely be higher. Emissions from moving/loading depend on organisation of transport and storage,

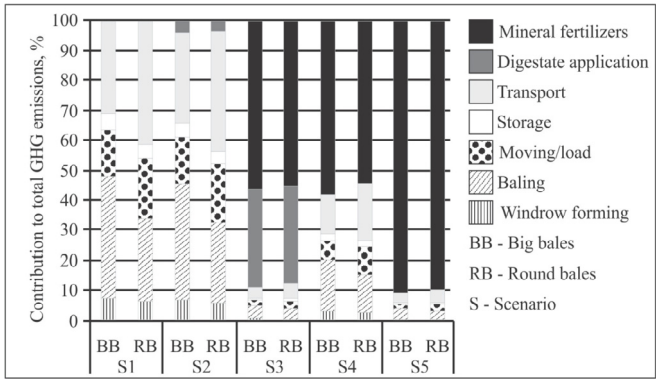

Fig. 1. Contribution of GHG emissions originating from different phases in total balance for analysed scenarios.

so they are also subject to change. In this case, two times bales loading and unloading are result of the primary and final storage existence. Emissions in these phases are, in basic scenario S1, up to 20% of total. The storage phase has the lowest emissions in comparison to others. These are result of a covering foil production and such a low emissions are result of considered multiyear use. It is not rare case that bales are stored without any cover foil, so emissions in this phase could be even zero. However, this is followed by higher DM loses.

Inclusion of the agricultural operation digestate application into system boundaries, S2 and S3, has shown that these associated emissions are about 600 gCO_{2eq}/tDM. It is important to emphasize that such low emissions are result of the fact that they are related only to corn stover in the digestate which represents a smaller part of the digestate mass. The remaining part is water or other co-substrates and is not subject of this study. It would be justifiable to include to them associated emissions only if complete system of production and utilisation of biogas from corn stover and other co-substrates is subject of the analysis.

If nitrogen in digestate is considered, like in S3, then some major effect on GHG balance can be noticed. Since entire amount of potassium and phosphorus removed by the collection of corn stover is

returned to field via digestate, there are no emissions associated to these two nutrients. Only N_2O emissions should be considered and then some major changes of GHG balance in comparison to S1 are obtained. For S3, amount of N_2O that is emitted during digestate spreading is almost 40,000 gCO_{2eq}/tDM. Due to these emissions, missing quantity of nitrogen should be replaced by mineral fertilizers and applied to the soil in order to compensate the lost nitrogen. As a consequence of nitrogen fertilizer application, again certain amount of N_2O is emitted and again GHG are emitted during its production. In total, consideration of nitrogen flow within the system results with app. eight time higher GHG emissions.

If digestate is applied to agricultural fields other than those from which stover was collected and nutrients flow and associated emissions taken into account, scenarios S4 and S5, substitution of potassium and phosphorus by mineral fertilizers emits app. 19,000 gCO_{2eq}/tDM. These emissions are completely generated in process of production of fertilizers. Difference between S4 and S5 originates from consideration of nitrogen. If entire amount of nitrogen removed from the field should be compensated by mineral fertilizers such as *e.g.* urea, resulting GHG emissions would be about 117,000 gCO_{2eq}/tDM. Around 40% of these emissions are result of fertilizer production and rest are direct and indirect emissions of N_2O. For S5, total emissions would be around 150,000 gCO_{2eq}/tDM.

When compared, GHG emission values for collection of corn stover and corn silage, that is most commonly used energy crop for biogas production, they are very similar for S3 and S5. GHG emissions of corn silage in cultivation phase adopted as default values in (European Commission, 2017b) are 16.2 and 16.5 gCO_{2eq}/MJ of produced biogas (two values are result of an analysed system definition). If stated emissions in S3, 125,000 gCO_{2eq}/tDM, are expressed per MJ of potentially produced biogas, value would be around 18 gCO_{2eq}/MJ. Similarly, for S5, this value would be around 22 gCO_{2eq}/MJ. Inclusion of nutrients and associated emissions places corn stover in category of energy plants in terms of GHG emissions.

Two parameters were varied for sensitivity analysis. Corn stover yield has influence on productivity of machinery used for windrow forming and baling. Productivity is lower if yield is reduced and vice versa. Lower stover yield increases diesel consumption in order that one ton of DM is processed. So, in terms of GHG emissions, balance is either negatively or positively influenced by decrease or increase of stover yield, respectively. These two phases in combination emit app. 3700 gCO_{2eq}/tDM. By taking into account applied variations of stover yield, for reduced and high stover yields emissions are app. 5500 and 2800 gCO_{2eq}/tDM, respectively. This means that roughly, one ton variation in corn stover DM's yield will change GHG balance between 600 and 800 gCO_{2eq}/tDM. Since total GHG emissions of entire stover collection cycle are much higher, it could be concluded that stover yield fluctuations does not represent influencing parameter. Influence of transport distance, or more precisely transport distance between place of primary storage and place of final use, is presented in Fig. 2. It could be seen that 20 km increase in transport distance as a result has app. 3500 gCO_{2eq}/tDM more GHG emitted if stover is baled in form of BB. In case of RB, emissions are about 5500 gCO_{2eq}/tDM increased for every 20 km longer transport distance.

In scientific publications there are analyses of the GHG emissions of corn stover based biogas or bioethanol in accordance to the LCA principles, but not in accordance to the RED method. Major issues are: expression of results per functional units other than the one stated in the RED method; accounting emissions from equipment production; consideration of the corn grain production within defined system boundaries and by this, incorporating emissions originating from agricultural operations prior to corn stover collection; tendency that the impact of corn stover removal

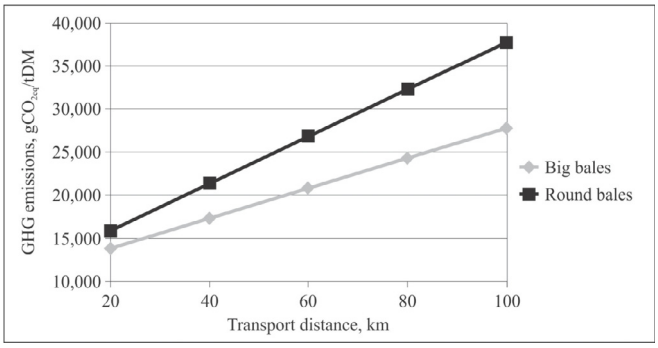

Fig. 2. Influence of transport distance to GHG emissions.

on soil is included in terms of GHG emissions together with stover collection. Results obtained in this study are comparable for analysed processes. For example, according to Manandhar and Shah (2017), transport of baled stover emits around 19,400 gCO_{2eq}/tDM for 113 km which is result almost identical with this study. Murphy and Kendall (2013) and Spatari et al. (2005) are stating that for stover collection and nutrients compensation, emissions are 88,000 and 97,000 gCO_{2eq}/tDM, respectively. Pourbafrani et al. (2014) are stating even lower emissions, 54,000 gCO_{2eq}/tDM by considering single-pass collection of corn stover and compensation of only nitrogen by mineral fertilizer. GHG emission balance for S5 is higher in comparison to these, similar studies and this is mainly consequence of emissions of N_2O. Quantity of emitted N_2O depends on selection of emission factors and type and quantity of considered mineral fertilizer. Here, emission factors for N_2O are based on those stated in IPCC, and in total, almost 2% of nitrogen is emitted directly or indirectly as N_2O. This emission rate can be seen as upper limit value. Giuntoli et al. (2015) have well elaborated impact of application of different, lower, emission factors. Authors like Rana et al. (2016) and Bachmaier et al. (2013) are also using lower emission factors for N_2O emissions, but nevertheless IPCC emission factors still remain generally accepted factors for this type of study.

Based on the four scenarios, defined with the goal of overcoming the RED method deficiencies, following is stated:

1. Emissions emerged from application of digestate on the same field from where stover is collected, which is the common case, are not significant and do not affect the overall emissions, so their inclusion into equation of RED method is not important. Flows of phosphorus and potassium also should not be included in this case because of closed loop.
2. If digestate is not used on the same field, the emissions, due to the compensation of phosphorus and potassium, should be included into RED method. Their values approximately double initial value of total GHG emissions for collection phase.
3. The analysis of nitrogen flow has the potential to increase the value of GHG emissions in collection phase considerably. Their inclusion into the equation of RED method is needed. Special attention should be given to the emission factor of N_2O. Scientific publications do not explicitly state what happens to the soil nitrogen balance if corn stover is left or removed. It is even harder to make conclusions how these practices influence emissions of GHG. The inclusion of nitrogen would probably even require defining a time frame for the analysis. In the long term, organic nitrogen in corn stover is, probably, gradually mineralized if it is left on field and enters the regular nitrogen cycle. By anaerobic digestion this transformation is more rapid. If digestate is returned to the field, even bonus of GHG emissions (subtraction) could be considered, since this reduced amount of nitrogen fertilizers needed for next crop on the same field.

4. Conclusions

According to rules of RED method, GHG emissions, up to the process of stover collection, are excluded from system boundaries. That is why removal of crop residues and its impact on soil characteristic are not included into this method. This has been overcome in this study by assessment of nutrients' flows and inclusion of GHG emissions originating as a consequence of application of mineral fertilizers or digestate.

If emissions are considered to be zero up to the process of stover collection, expected GHG emissions are around 9500 gCO_{2eq}/tDM. To this value should also be added emissions emerged during transport of raw corn stover, which depend on distance. Bales form does not have significant influence for short transport distances. With increase of distance, big rectangular bales have advantage over round bales in terms of GHG emissions due to better utilisation of transport capacities. Corn stover yield is not significant influencing factor for value of GHG emissions.

It is recognised that GHG emissions generated during corn stover collection are strongly influenced by definition of system boundaries. Emissions associated with nutrients and especially nitrogen flows, have tendency to significantly increase GHG emissions of corn stover collection and even to take sustainability of utilisation of this substrate into question. Main issue is whether nitrogen flows and associating emissions should be considered. Anaerobic digestion has tendency to transform nitrogen contained in corn stover, mainly in form of bio-molecules, into form of nitrogen which can be used by plants. If corn stover is not used in biogas plant, but remains on the field, this nitrogen mineralisation lasts longer. According to obtained results, total GHG emissions, if nitrogen, potassium and phosphorus are taken into account, rise up to app. 150,000 gCO_{2eq}/tDM for scenarios when digestate is used on other fields. Consideration of only phosphorus and potassium raises GHG emissions up to 35,000 gCO_{2eq}/tDM. In case when digestate is used on the same fields from where corn stover is collected, emissions are up to 125,000 gCO_{2eq}/tDM for all three considered nutrients or up to around 16,000 gCO_{2eq}/tDM when only phosphorus and potassium are considered. Lower emissions in scenarios when digestate is returned to the same fields from where corn stover is collected are justifying such digestate management practice.

Further investigation should be oriented to give definite conclusion if emissions originating from nitrogen nutrient should be included in studies like this one. Also, expansion of system boundaries by adding processes of biogas production and utilisation should give plausible answer about sustainability of corn stover utilisation as biogas substrate in line with the Renewable Energy Directive.

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